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Hydraulic Resistance and Flow Pattern at Design and Off Design Flow Rates Among Axial Flow Machines

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HYDRAULIC RESISTANCE AND FLOW PATTERN AT DESIGN AND OFF DESIGN FLOW RATES AMONG AXIAL FLOW MACHINES

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Abstract

In an axial flow machine, fluids flow condition, that is flow pattern in a rotating flow passage changes its form and magnitude by the hydraulic resistance to the fluid flow in flow passage. Effect of centrifugal force becomes stronger with the increase of hydraulic resistance, and the flow rate becomes smaller. And, in the comparison of fluids flow condition among different axial flow machines, if the efficiency at an equivalent flow rate differ one another, then on the favorable machine in efficiency grade, the effect of centrifugal force to the fluids flow pattern, formed in the flow passage, appears much obviously. With the decrease in flow rate this tendency becomes stronger as much the difference of efficiency grade becomes larger. All these relations may be held among axial flow machines, regardless to operating condition whichever they are operated at design or off design condition.

1. INTRODUCTION

All the axial flow machines flow passages are formed in a conduit pipeline. Therefore, all the internal flow condition of our interest, observed in an axial flow machine, could be considered quite equivalent to flow condition, generally formed in a conduit pipeline [1].

On the other hand, in a practical operation, flow rate at which each of upstream and downstream backflows starts at lower flow rate region at off design flow rate differ one another among axial flow machines. They are same as that backflows characteristics at an equivalent flow rate differ each other at off design condition. In addition, interrelation between the internal flow condition in rotating flow passage and the pump efficiency, at an equivalent flow rate, differ one another among axial flow machines. Therefore, at a glance, it seems that their interrelation has been compricated in the practical operation. Their interrelation has been investigated by many investigators, and reported such as those by Lakshminarayana (1973), Tanaka (1988), Engeda (1988), and so on.

Genarally, it is believed that internal flow condition is regularly interrelated with pump efficiency in operation of axial flow machine [2,3]. Experimental interrelation between the occurrence of backflow phenomena and the efficiency characteristics at off design condition among axial flow machines is reported by Tanaka (1982). However, relative interrelation with flow pattern among axial flow machines has not been clear from these previous investigations [4,5]. From these view points, fundamental interrelation between hydraulic resistance and flow pattern at design and off design condition among axial flow machines are discussed in this paper. And from fundamental interrelation, obtained in this discussion, an useful flow model to be taken at theoretical analysis is suggested.

2. GEOMRTRICAL SHAPE OF FLOW PASSAGE AND INTERNAL FLOW CONDITION

In the practical comparison of two different axial flow machines, their suction head may be kept at an equivalent constant value for any operation flow rate condition. Then, in an axial flow machine, whose efficiency characteristic is favorable, its produced head at impeller discharge, at an equivalent flow rate, becomes larger than that for less favorable machine, regardless to flow rate whichever they are operated at design or off design flow rate.

Therefore, if in two axial flow machines their total geometrical flow passages, except those at impelling blade section, are made identical, then to accomplish the equivalent flow rate, as a matter of course, hydraulic resistance to fluid flow has to be made stronger for favorable axial flow machine than that for less favorable axial flow machine, as much the efficiency is much favorable.

In practical operation of axial flow machine, it is well known that to control the operating condition, hydraulic resistance to the fluid flow is forcibly increased at the location of discharge valve, then the flow rate is decreased with the decrease of cross area. This indicates that cross area, at an equivalent flow rate, has to be closed in the flow passage much tight (narrower) at the location of discharge valve for favorable axial flow machine than that for less favorable axial flow machine, as much the efficiency is much favorable.

On the other hand, in the practical operation, geometrical shape of flow passage in the region between impelling section and discharge valve is changed forcibly by discharge valve with the decrease in flow rate so that it constructs (forms) a kind of semi closed vessel with a rotating impeller in it. Then, it may form a flow passage (geometrical shape) much similar to closed vessel than that for less favorable axial flow machine, as much the efficiency is much favorable. At zero flow rate, flow passage performs a fully closed vessel with a rotating impeller in it.

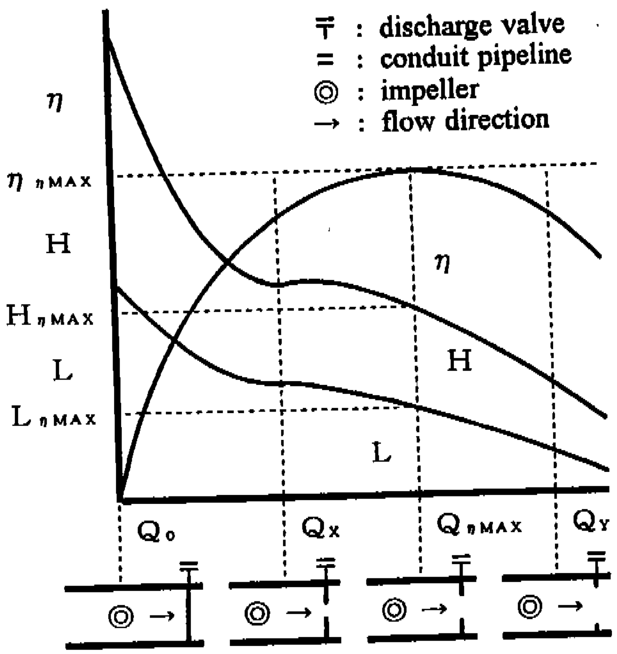

Fig.1 Performance characteristics curve of an axial flow rotating machine and geometrical shapes of flow passage in a conduit pipeline.

This indicates that in an axial flow machine, flow passage is closed by the discharge valve, and flow rate is decreased. Then, as a rotating impeller is installed in it, as a matter of course, centrifugal forces may act to fluid particles in the flow passage regardless to flow rate, at whole operating range of flow rate from the largest flow rate to zero flow rate. And, it may be clear that on the favorable axial flow machine in efficiency characteristics, centrifugal force acts to fluid particles stronger than those for less favorable axial flow machine, as much the efficiency is much favorable, both at design and off design flow rates.

3. ESTIMATION OF INTERNAL FLOW CONDITION

In practical operation of an axial flow machine, discharge valve is fully opened in the flow passage at the largest flow rate Q_{max}. However, it could be consider that even if the flow passage is fully opened at the largest flow rate, some resistance to fluid flow may be caused in the conduit pipeline and some centrifugal force which acts to fluid particles may exist in the flow passage. That is, even if the cross area is fully opened at the largest flow rate Q_{max}, as far as a rotating impeller is set in the conduit pipeline, it would be natural and reasonable to consider that some centrifugal force exists and acts to fluid particles, and their magnitude differs by the grade of internal flow condition, that is by the pump efficiency among axial flow machines.

Generally speaking, with the decrease in flow rate, cross area is closed gradually in the flow passage by discharge valve. This indicates that with the start to decrease its largest flow rate, flow passage starts to form a geometrical shape similar to closed vessel. And, at zero flow rate, cross area is fully closed, and flow passage forms a fully closed vessel. That is, centrifugal force starts to increase with the start to decrease its largest flow rate, and may finish their interrelation at zero flow rate. This geometrical flow passages change, caused by a discharge valve may indicate the future of internal flow condition as that centrifugal force increases in the flow passage continuously with the decrease in flow rate from the largest flow rate to zero flow rate. Therefore, it could be said that effect of centrifugal force may be the smallest at the largest flow rate and the strongest at zero flow rate.

In an axial flow machine, cross area becomes narrower with a decrease in flow rate, and effect of centrifugal force increases. However, at some opening of discharge valve, that is at a certain value of flow rate between fully opened and fully closed conditions, its operating (impelling) condition, that is the shape of flow passage of a conduit pipeline becomes most convenient (optimum).

That is, at a certain value of flow rate, on the way to decrease its flow rate from the largest to zero, that is, at a certain flow passages shape similar to (semi) closed vessel, its operating condition becomes most convenient. That is, on the way increasing the effect of centrifugal force, at a certain flow condition with a certain effect of centrifugal force, its internal flow condition becomes optimum (convenient). It would be obvious that this flow condition corresponds to maximum efficiency point. Therefore, it could be concluded that at maximum efficiency point there are some effect of centrifugal forces in the flow passage of axial flow machine.

4. HYDRAULIC LOSSES AND CENTRIFUGAL FORCE

In practical operation of high specific speed axial flow machine, it is obvious that flow condition becomes most convenient at maximum efficiency points. Therefore, it seems that all the fluids may flow in the flow passage, most closely following the impeller blade shape of flow passage at maximum effifiency point. In other words, as all the axial flow machines are designed so that impelling blades direct fluids forcibly to flow toward axial direction, it could be considered that all the fluids may flow toward axial direction at maximum efficiency point. This may induce the assumption that in an axial flow machine there is no radial flow in flow passage of conduit pipeline and that there is no effect of centrifugal force at design condition.

However, the results obtained here indicate that centrifugal force may increase its magnitude certainly and continuously in the flow passage with a decrease in flow rate from the largest flow rate to zero flow rate, and it may not become the minimum at the maximum efficiency point. Because, geometrical area ratio at the maximum efficiency point is fairly smaller than that at the largest flow rate.

This indicates that for the improvement of efficiency characteristics in axial flow machines, the fluid flow condition at the maximum efficiency point which effected by centrifugal force may need to be considered in theoretical analysis.

5. INTERRELATION WITH PERFORMANCE CHARACTERISTIC CURVE

If we look at practical operating condition of an axial flow machine, it is obvious that flow rate at maximum efficiency point situates quite downstream from that of the largest flow rate.

Then, it would be reasonable to consider that effect of centrifugal force at the maximum efficiency point is quite larger than that at the largest flow rate. Over against this, at the maximum efficiency point, hydraulic energy losses may become smaller than that at the largest flow rate. It may take a smallest value at the maximum efficiency point.

On the other hand, it is believed that centrifugal force may increase its magnitude regularly in the flow passage with the increase of hydraulic energy losses. If we look at the operating condition in the region between the flow rate at the maximum efficiency point and zero flow rate, then with the decrease in flow rate, centrifugal force may increase its magnitude regularly in the flow passage with the increase of hydraulic energy losses. This result may consist with general concepts.

However, if we look at the operating condition in the region between the largest flow rate and the flow rate at the maximum efficiency point, it may be obvious that hydraulic energy losses decrease certainly and continuously with the decrease in flow rate from the largest flow rate to flow rate at the maximum efficiency point. Hydraulic energy losses may take the smallest (minimum) value at the maximum efficiency point. That is, for the decrease in flow rate, although the hydraulic energy losses become smaller than that at the largest flow rate, the magnitude of centrifugal forces becomes larger than that of the largest flow rate. This result may be opposed to general consepts.

These two comparable results for the decrease in flow rate, one is accord and the other is opposed to general concepts, may indicate that centrifugal forces and hydraulic energy losses may not regularly interrelated for different flow rates in a axial flow machine.

6. FUTURE OF INTERNAL FLOW CONDITION

Above description indicates that all the axial flow machines, operated at each maximum efficiency point, are definitely under the flow condition whose cross area is semi closed at the location of discharge valve. And centrifugal force, caused by rotating impeller may act forcibly to fluid particles in the flow passage. Their magnitude may differ among different axial flow machines by the relative grade of internal flow condition, that is by the relative grade of efficiency characteristics.

If we compare centrifugal forces, for example, at the maximum efficiency point among different axial flow machines, then it may be obvious that their magnitudes may become stronger for favorable efficiency axial flow machine than those for less favorable efficiency machine. Because geometrical area ratio at cross section of discharge valve to that at free conduit pipeline, at an equivalent flow rate, has to be set at a smaller value for favorable efficiency axial flow machine than that for less favorable efficiency machine. It must be set at a smaller value as much the relative grade of efficiency characteristics is much favorable.

This indicates that for favorable axial flow machine in efficiency characteristics, centrifugal force may act stronger than that for less favorable axial flow machine. That is, for the axial flow machine with a small hydraulic energy losses, centrifugal force may act stronger than that with a large hydraulic energy losses. Because, at an equivalent flow rate, the better the efficiency characteristics become, the smaller the hydraulic energy losses become among different axial flow machines. These relations may be held regardless to operating condition whichever they are compared at design or off design condition.

Fig. 2 shows two flow models. Their length of flow region in the conduit pipeline between the impelling section and the discharge valve section is same. Diameters are also same. But cross area ratio at discharge valve to that at free conduit pipeline is different. These flow passages, each has a rotating impeller, may construct various semi closed flow passages for various flow rates. Their relative grade of efficiency characteristics is assumed here different. The flow model, whose cross area ratio at discharge valve is small, indicates favorable axial flow machine, and the other model, whose cross area ratio is large, indicates less favorable axial flow machine. For imaginary comparison, internal flow conditions, estimated from above discussion, are illustrated in the flow passage.

Therefore, it is clear that on the favorable high specific speed axial flow machine in efficiency characteristics, centrifugal force caused by rotating impeller at an equivalent flow rate may act to fluid particles stronger than that for less favorable axial flow machine.

It may be stronger in the flow passage as much the relative efficiency grade is much favorable. In other words, on the favorable axial flow machine in efficiency characteristics, hydraulic force caused by rotating impeller, such as radial forces which direct fluid particles from inner radius towards outer radius and tangential force which rotate fluid particles around impeller axis, may act stronger in the flow passage than those for less favorable axial flow machine.

Accordingly, in the high specific speed axial flow machine with a favorable efficiency characteristics, as the hydraulic energy losses are smaller, axial flow velocity may become larger at outer radius and smaller at inner radius in the flow passage of conduit pipeline than those of less favorable efficiency axial flow machine. These tendency may become obvious to appear as much the relative difference of efficiency characteristics: favorable and less favorable at an equivalent flow rate becomes larger. These interrelation may be held in the flow passage regardless to flow rate whichever they are compared at design or off design flow rate.

From these discussion it could be summarized that on the favorable high specific speed axial flow machine in efficiency characteristics, as hydraulic energy losses at maximum efficiency point are smaller than those for less favorableaxial flow machine, centrifugal force may act to fluid particles stronger than that for less favorable axial flow machine, and this tendency may become stronger as the hydraulic energy losses become smaller. These results may be held regardless to operating condition whichever they are compared at design or off design condition.

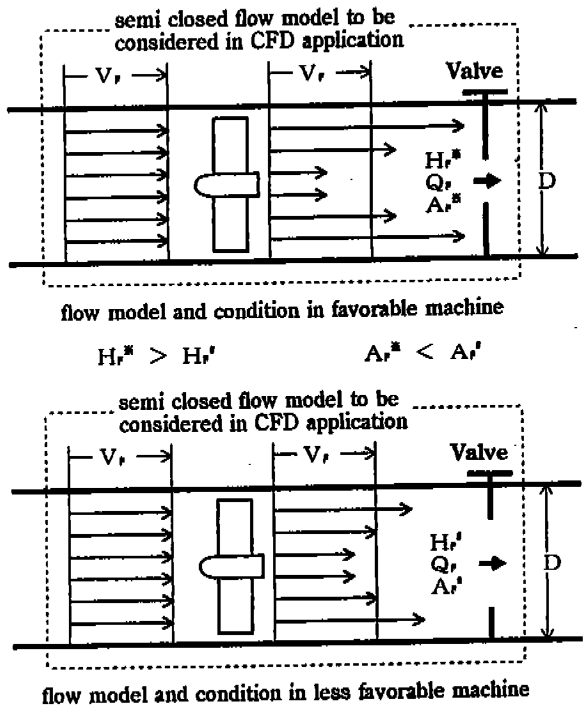

Fig. 2 Flow models, generally taken for fluid flow analysis in conduit pipeline with a rotating impeller in it and a semi closed flow passage at an equivalent flow rate Q_F for practical operation of two axial flow machines: above is for favorable axial flow machine & below is for less favorable axial flow machines.

7. FLOW MODELS, GENERALLY TAKEN IN FLOW PASSAGE

From the above discussion, it became clear that on the favorable axial flow machines in efficiency characteristics, discharge head, produced at an equivalent flow rate, may always become larger than those produced by less favorable axial flow machines, regardless to flow rate whichever they are operated at design or off design flow rate. These are the meaningful and useful results obtained from previously discussion of this paper by the comparison of hydraulic energy outputs at an equivalent flow rate between favorable and less favorable axial flow machines in practical efficiency characteristics.

However, if we look at the geometrical boundary conditions in flow passage of conduit pipeline, it is clear that geometrical cross area ratios of cross section at location of discharge valve to that at free conduit pipeline at an equivalent flow rate may be always set at different values between those two different kinds of axial flow machines in efficiency characteristics. That is, for the favorable axial flow machines in efficiency characteristics, those geometrical cross area ratios may be always set at smaller values than those for less favorable axial flow machines.

Here, the geometrical cross area ratio at the location of discharge valve may have an equivalent meaning with the geometrical boundary condition between impelling blade section and discharge valve section in the flow passage of conduit pipeline. Then, it could be said that these comparison about the hydraulic energy outputs at an equivalent flow rate may not be made under the equivalent geometrical boundary conditions between favorable and less favorable axial flow machines in efficiency characteristics.

All the axial flow machines may vary their operating condition by the hydraulic resistance which acts on fluid particles in flow passage of conduit pipeline. In practical operation of axial flow machines, the performance characteristic curves may be obtained from the fluid flow condition, formed in the flow passage of conduit pipeline with a rotating impeller in it. Its geometrical boundary condition may vary with the increase in hydraulic resistance at the location of discharge valve from the largest cross area (same to cross area at free conduit pipeline) to the smallest cross area (zero cross area).

And all the operating conditions, that is all the internal flow condition, which followed to each of those various geometrical boundary conditions change, may be obtained for various hydraulic resistances between the largest flow rate at the smallest hydraulic resistance and the smallest (zero) flow rate at the largest hydraulic resistance in practical performance characteristic curves.

Therefore, in an axial flow machine its operating condition varies with the increase in hydraulic resistance from the fully opened condition to the fully closed condition of discharge valve. The geometrical cross area ratio of cross section at the location of discharge valve to that at free conduit pipeline may decrease from the fully opened condition to the fully closed condition with the increase in hydraulic resistance. That is, geometrical boundary condition of conduit pipeline, with a rotating impeller in it, may change its form from the open type conduit pipeline to the closed type conduit pipeline with the increase in hydraulic resistance.

Therefore, it could be said that their internal flow condition, that is fluid flow condition may be always set, at least, under the condition affected by geometrical boundary condition. This geometrical boundary condition may affect stronger to fluid flow condition in flow passage with the increase in the hydraulic resistance from the resistance at the fully opened condition to resistance at the fully closed condition of the discharge valve.

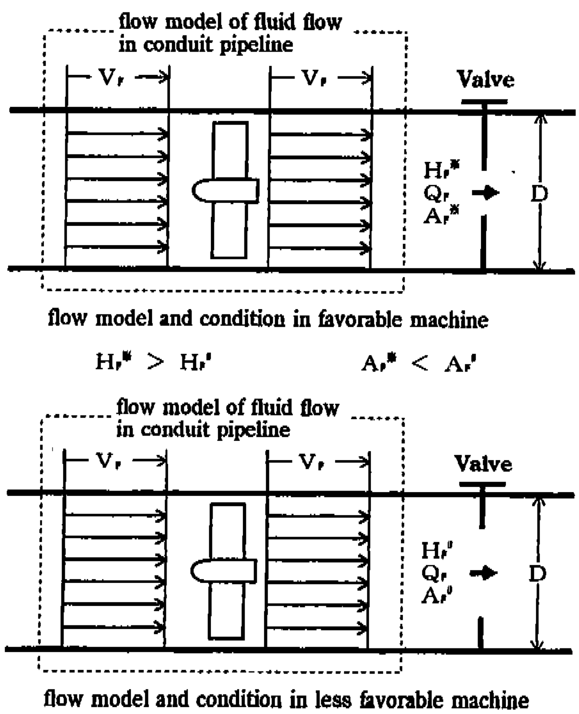

Fig. 3 Flow models for fluid flow in conduit pipeline with a rotating impeller in it and a semi closed flow passage at an equivalent flow rate Q_F for practical operation of two axial flow machines: above flow condition is for favorable axial flow machines and below is for less favorable axial flow machines.

Then, in the flow passage of pumping system it could be said that internal flow condition, that is flow pattern and its magnitude, may vary with the increase in hydraulic resistance from flow pattern at the smallest resistance to flow pattern at largest resistance. The effect of geometrical boundary condition may be the smallest at former flow pattern, and the largest at latter flow pattern. Therefore, it could be said that the smaller the geometrical cross area ratio becomes, the stronger the effect of the geometrical boundary condition becomes. In other words, with the change in the hydraulic resistance, the flow pattern and its magnitude may change together with, following the geometrical boundary condition at the flow passage. That is, the stronger the hydraulic resistance becomes, the flow pattern may be formed in the flow passage so that the stronger the effect of centrifugal forces becomes and the smaller the total flow rate becomes.

From previous discussion it may be clear that on the favorable axial flow machines in efficiency characteristics, geometrical cross area ratios at location of discharge valve at an equivalent flow rate is always set at a smaller value than those for less favorable axial flow machine, regardless to operating condition whichever they are operated at design or off design condition. Then, it could be said that on the favorable axial flow machines their flow condition (flow pattern) at an equivalent flow rate may be always put under the condition at which centrifugal foeces may affect to fluid particles stronger than those for less favorable axial flow machines, regardless to the operating condition whichever they are operated at design or off design condition.

From above discussion it could be said that in the practical operation of an axial flow machine, fluid flow condition, that is flow pattern may be varied its form and magnitude by hydraulic resistance in flow passage by changing the geometrical cross area ratio at the location of discharge valve, and that they may also differ among axial flow machines by the grade of efficiency characteristics. In an axial flow machine, with the increase in hydraulic resistance, that is with the decrease in the geometrical cross area ratio, the flow pattern may change its form and magnitude so that the larger the effect of the centrifugal forces becomes and the smaller the total flow rate becomes.

And, if the grade of the efficiency characteristics at an equivalent flow rate differ among axial flow machines, then on the favorable axial flow machines in efficiency characteristics their flow pattern may be formed in the flow passage so that the larger the effect of centrifugal forces becomes. This tendency may become stronger as much the difference of those grades becomes larger in efficiency characteristics. All these relations may be held regardless to operating condition whichever they are operated at design or off design condition.

8. CONCLUSIONS

From the above discussion it could be concluded that in an axial flow machine, fluids flow condition, that is flow pattern may change its form and magnitude so that the larger the effect of centrifugal forces becomes and the smaller the total flow rate becomes with the increase in hydraulic resistance. And, if the grade of efficiency characteristics at an equivalent flow rate differ among the axial flow machines, then on the favorable axial flow machines in efficiency characteristics their flow pattern may be formed in the flow passage so that the larger the effect of centrifugal forces becomes. This tendency may become stronger as much the difference of those grades becomes larger in efficiency characteristics. All these relations may be held regardless to operating condition whichever they are operated at design or off design condition.

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